Estimating Background Loads of Sediments, Organic Nitrogen, and Organic Phosphorous in the Mississippi River Basin

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Abstract

Estimating Background Nutrient Loads in the Mississippi River Basin Using Loading Functions and a GIS

The primary source of measured data available for sediment and nutrient loading on a national scale is found in the stream data published by the USGS (USGS, 1991). However, this data does not provide much information about whether the loadings come from point, nonpoint, or background sources or about where the sources are located. Hydrologic modeling can be used to provide much additional information about probable sources of pollutants and how they are transported through surface water and ground water systems.

USDA/NRCS and TAES have initiated a national scale modeling project to estimate the nonpoint source pollutant loadings (sediment and organic nutrients) from agricultural areas and other land uses in the 48 coterminous United States. We also hope to incorporate existing data on point source loadings in our national modeling effort. Some preliminary results for the Mississippi River Basin from this study will be presented in this paper.

The primary modeling unit areas for this project are the USGS' *Hydrological Cataloging Units (8-digit watersheds)*. A GIS (GRASS) is being used with national and regional scale topographic, soils, and land use databases. Interface programs have been developed to link these GIS databases with soil and water assessment models. One model used to estimate sheet and rill erosion rates is the Universal Soil Loss Equation (USLE). In this preliminary, generalized approach, the amount of sediment reaching the water bodies has been estimated by applying a drainage area dependent delivery ratio to the USLE based erosion estimates. Then the amount of organic nutrients was estimated using a sediment enrichment ratio for each nutrient (N and P) based on the organic carbon content of the eroded soils.

This simple generalized procedure provides preliminary estimates of background loadings of sediments, organic nitrogen, and organic phosphorous, not accounting for point source loadings or contributions from the uses of fertilizers in the river basin.

Introduction

The Resources Conservation Act of 1977 (RCA) authorizes the Department of Agriculture (USDA) to appraise the current condition and trends in the uses and conservation of soil, water, and related natural resources on non-federal lands in the nation each decade. The Third RCA Appraisal is due in 1997. The RCA Appraisals are supposed to provide information to be used in developing updates to the USDA National Conservation Program (NCP). The NCP is a public statement of policy of which activities will have the highest priorities for USDA agencies for natural resources conservation activities on non-federal areas.

The Natural Resources Conservation Service (NRCS), the Agricultural Research Service (ARS), the Texas Agricultural Experiment Station (TAES), and other agencies are cooperating on a Project for Hydrologic Unit Modeling of the United States (The HUMUS Project). This Project is designed to develop a weather-driven model of soil-plant-water interactions and to route water flow, erosion, sediment flow, nitrate flow, phosphate flow, and salt transport through the major river basins of the 48 conterminous States for the RCA Appraisal. We started the HUMUS Project in 1992 and will complete it in 1996 or early 1997. We expect, however, that the technology we are using will still be in its infancy. We expect to improve this technology over time and for it to be used by ourselves and others at a wide range of scales from small watersheds to international river basins.

The hydrological model we are using is the Soil and Water Assessment Tool (SWAT) developed by the Grasslands, Soil and Water Research Station of ARS at Temple, Texas. This is a comprehensive but somewhat generalized model of surface water runoff, groundwater return flows, and streamflow dynamics that integrates estimates for small subwatersheds into estimates of flows in major river basins. The SWAT can operate with historical weather data or with a series of synthetically generated weather patterns. The model includes options for simulating ponds, major reservoirs, and wetland areas in the system. The SWAT is scale independent, but the accuracy of the derived flow estimates depends directly on the accuracy of the available data, including data on weather, topography, channel dimensions, reservoir dimensions, reservoir operating rules, soils, land cover, crops, on transpiration rates from crops and natural vegetation through the dormant and growing seasons, etc.

We are using the Geographic Resources Analysis Support System (GRASS) geographic information system (GIS) as our primary tool to manage and manipulate the databases we have assembled from USGS, the Weather Service, NRCS, and other sources, on weather, topography, land cover, soils, crops, stream locations, watershed boundaries, political boundaries, water quality, etc.

Dr. Srinivasan has written an interface program to use GRASS and the databases to develop input data sets for the SWAT model. He is also developing a GRASS-based, report-writing interface program to help analyze and display the results of the modeling in both graphical and tabular formats. We also use the INFORMIX relational data base system for filing and querying some of our databases, especially those having to do with soil properties and with agricultural production and practices. Other GIS from available commercial sources may also be linked to the SWAT.

Early in the development of the HUMUS Project, we experimented with a short-cut approach for estimating background transport of sediments, organic nitrogen, and organic phosphorous. This preliminary work was based on using an earlier version of the SWAT instead of the more comprehensive water and sediment routing subroutines included in the SWAT. This approach uses our basic databases on topography, soils, crops, and land cover, but shortcuts the flow routing algorithms and uses generated, not actual, weather data. Other simplifying assumptions used were that all trees are evergreen trees and all crops were minimum tilled.

Figure 82 shows the resulting estimate of average annual rates of sheet and rill erosion caused by water runoff. The units on this map are metric, but 7.5 to 12 metric tonnes per hectare corresponds roughly to 3 to 5 English tons per acre, the normal range for so-called cropland erosion tolerance or "T" levels established by NRCS. Figure 83 is the same map with only four colors. Green represents areas where sheet and rill erosion is less than 3 tons/acre/ year. Blue represents areas where erosion rates are 3 to 5 tons per acre per year. And red areas show where sheet and rill erosion rates can't be kept to less than 5 tons per year even with minimum tillage on cropland.Table 8 lists the average sheet and rill erosion rates derived with our short-cut method for the 6 major river basins in the Mississippi River Basin. These data suggest that over 1 billion tons of soil are detached from the land surface of the Basin by sheet and rill erosion in an average year. These data also reveal that while the Tennessee River Region, which has only 11 percent of its area in cropland, has the highest rates of sheet and rill erosion. Nevertheless, this relatively small Region has the least total tonnage eroded. Conversely, the Missouri Region, though having the lowest average erosion rate, and about 30 percent of its area in cropland, ranks second in total tonnage eroded. The Upper Mississippi Region ranks third in total area and first in percent of its area in cropland, but fourth in its unit area average rate of erosion.

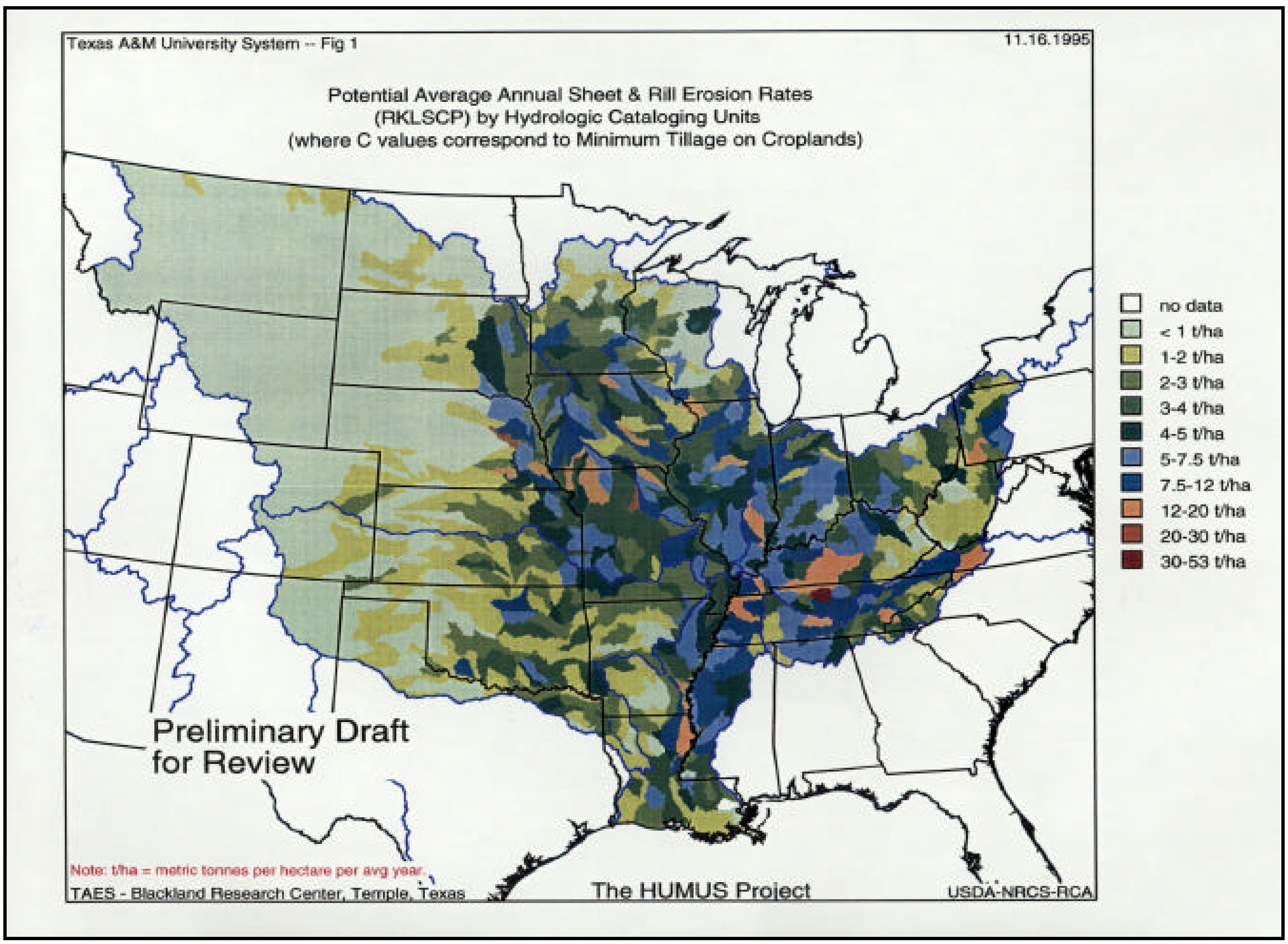

Figure 82.

Resulting estimate of average annual rates of sheet and rill erosion caused by water runoff.

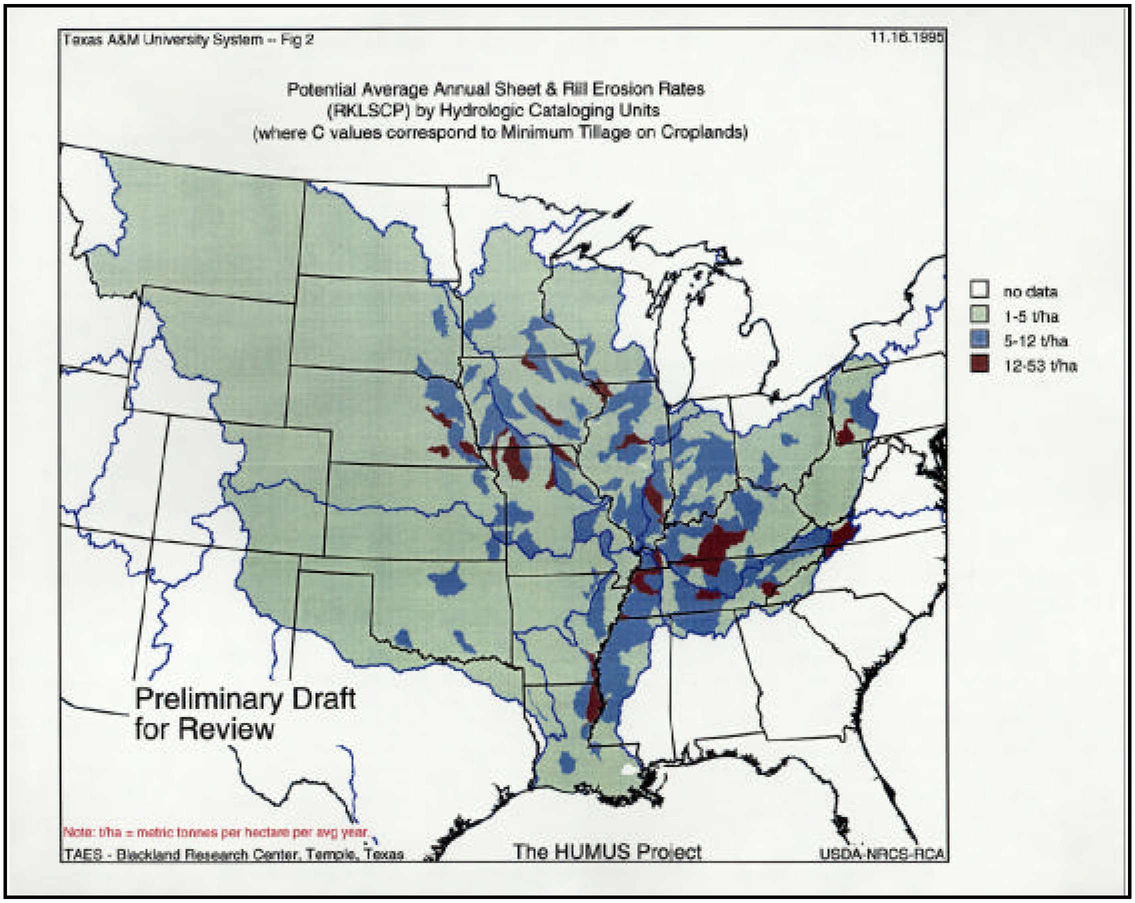

Figure 83.

Resulting estimate of average annual rates of sheet and rill erosion caused by water runoff.

Table 8.

Preliminary estimates of sheet and rill erosion.

Reg.	Hydrologic Regions	Average Annual Erosion Rates		
		Tons/Year	Tons/Acre	Tons/Sq. Mile
5	Ohio River	239,932,000	2.31	1477
6	Tennessee River	63,699,000	2.44	1559
7	Upper Mississippi River	229,509,000	1.9	1213
8	Lower Mississippi River	137,991,000	2.13	1362
10	Missouri River	230,440,000	0.71	453
11	Arkansas–White–Red Rivers	126,719,000	0.8	513
	Totals	1,028,290,000	1.29	823

Table 9 and Figures 84 and 85 present theses data in terms of the relative proportion each of the regions contributes to the total Mississippi River Basin load.

Table 9.

Comparing proportional erosion loads to drainage areas.

Reg.	Hydrologic Regions	Drainage Areas		S&R Eros.
		Square Miles	% of Area	% Erosion
5	Ohio River	162,439	12.99%	23.33%
6	Tennessee River	40,864	3.27%	6.19%
7	Upper Mississippi River	189,189	15.13%	22.32%
8	Lower Mississippi River	101,283	8.10%	13.42%
10	Missouri River	509,172	40.73%	22.41%
11	Arkansas–White–Red Rivers	247,195	19.77%	12.32%
	Mississippi River Basin	1,250,142	100.00%	100.00%

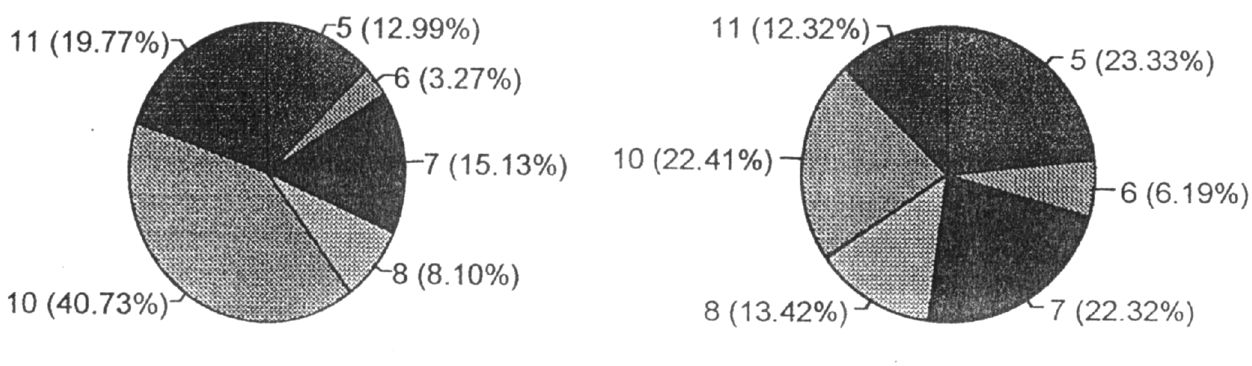

Figure 84.
Charts depicting hydrologic region areas in the Mississippi River Basin (left) and sheet and rill erosion rates by hydrologic regions (right).

Comparing to the NRI

The NRCS has another method for estimating erosion rates, one that has been used since the late 1950's. It is now called the Natural Resources Inventory (NRI). The NRI is a nationwide statistical site sampling procedure designed to make general estimates of erosion rates on non-Federal agricultural lands. The NRI has the advantage of having a detailed set of data on crop and land management practices at a large number of sample sites. Its major disadvantage is that it does not provide complete information about erosion rates on Federal lands or forest lands. This leaves fairly large areas unevaluated, as shown in Table 10a.

Nevertheless, the NRI reports include basin-wide estimates of tons of erosion based on the samples taken in the inventoried areas. Table 10b and Figure 86 show how our preliminary estimates of regional sheet and rill erosion rates compare to the rates reported in the 1992 NRI.

Table 10a.

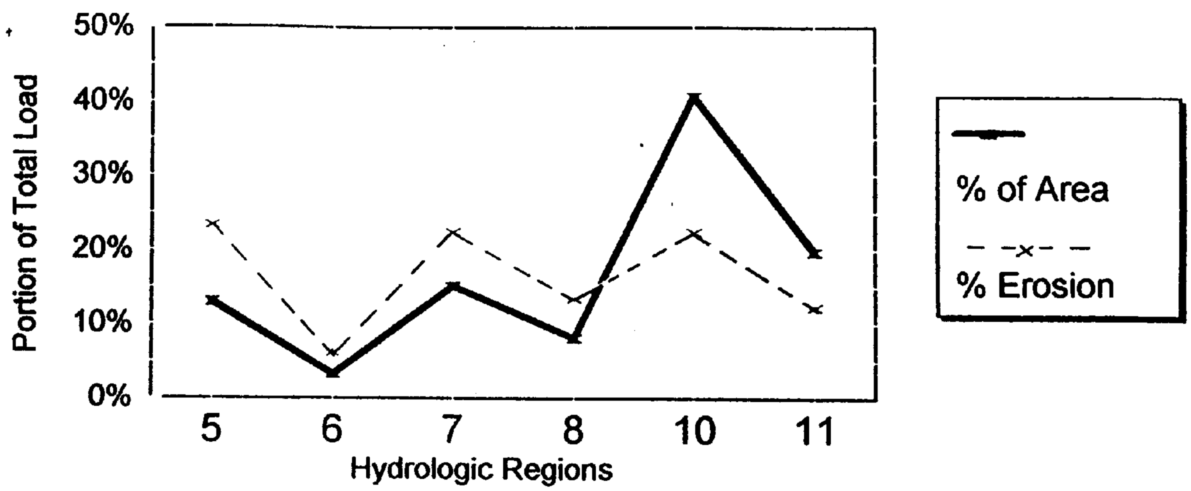

Figure 85.
Relative rates of sheet and rill erosion by hydrologic regions.

Areas reported for erosion in the NRI.

Reg.	Hydrologic Regions	Total Acres	NRI Report Acres	% Reported
5	Ohio River	103,960,758	49,927,300	48%
6	Tennessee River	26,153,159	8,437,800	32%
7	Upper Mississippi River	121,081,008	84,967,500	70%
8	Lower Mississippi River	64,821,123	31,058,800	48%
10	Missouri River	325,869,927	259,150,700	80%
11	Arkansas–White–Red Rivers	158,204,925	117,138,400	74%
	Totals	800,090,900	550,680,500	69%

Table 10b.

Comparing sheet and rill erosion estimates.

Reg.	Hydrologic Regions	HUMUS Tons/Year	NRI 1992 Tons/Year
5	Ohio River	239,932,000	254,904,360
6	Tennessee River	63,699,000	26,732,160
7	Upper Mississippi River	229,509,000	283,742,740
8	Lower Mississippi River	137,991,000	110,043,360
10	Missouri River	230,440,000	491,417,420
11	Arkansas–White–Red Rivers	126,719,000	176,426,730
	Totals	1,028,290,000	1,343,266,770

The NRI erosion estimates are significantly lower than the HUMUS estimates in the Tennessee and Lower Mississippi Regions. This could be attributed to the large portions of these areas under forest cover and thus unreported by the NRI. In the other three regions, especially in the Missouri Region, the NRI estimates are significantly higher than the preliminary HUMUS estimates. The HUMUS estimates are based on having all croplands in minimum till and the NRI estimates are based on actual tillage conditions in 1992. The differences in the estimates might imply a policy regarding promotion of minimum tillage. If these data are reasonably close to reality, the higher priorities for promoting minimum tillage to reduce erosion might better be focused in the Missouri and Arkansas-White-Regions than in the Corn Belt.

In the SWAT, there is an algorithm for estimating edge-of-watershed runoff of sediment. This load of sediment is called "Wash Load" in this paper,

Sedimentation

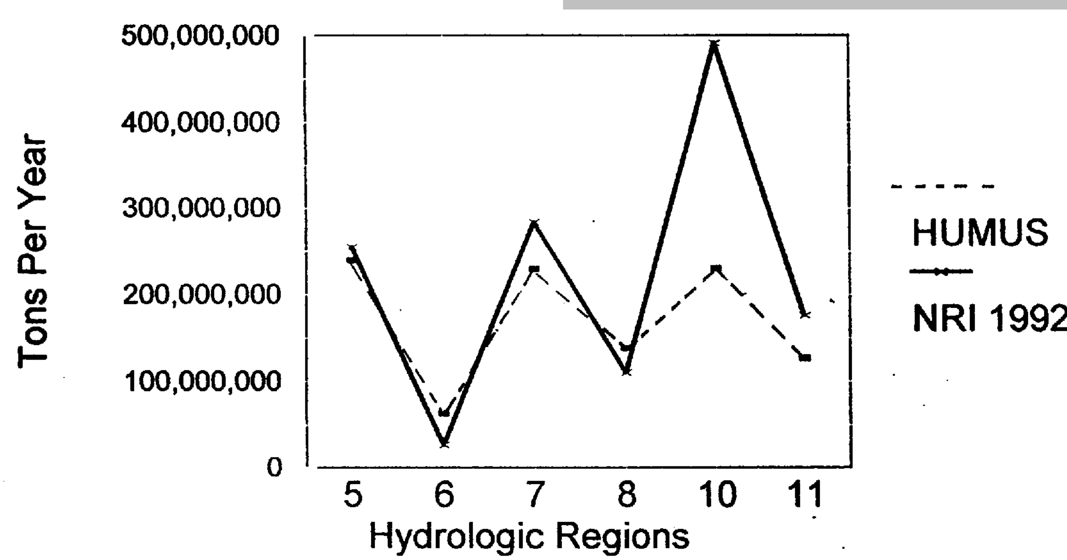

Figure 86.
Comparing S&R erosion rates by hydrologic region.

though this is a plagiarized term here. The coefficients of sediment delivery are based on the available literature, the gist of which is that the delivery ratio is an inverse function of the logarithm of the drainage areas. The delivery ratios used in this preliminary set of HUMUS Project sedimentation estimates are computed from the drainage areas of each of the contributing hydrologic cataloging unit (8-digit) areas.

When all of the sediment deliveries from these areas are lumped to produce sediment runoff estimates for the Hydrologic Regions, the composite delivery ratio for all of the Regions is about 5 percent.

Table 11a displays the preliminary HUMUS Project estimates of sediment wash loads.

For comparison, the regional composite sediment delivery ratios computed from the HUMUS Project data were applied to the NRI estimates of sheet and rill erosion to derive NRI-based sediment wash load estimates. The resulting hypothetical estimates are presented in Table 11b.

Table 11a.

Estimated average annual sediment "wash" loads.

		HUMAS Preliminary Estimates		
Reg	Hydrologic Region	Tons/Year	Tons/Acres	Tons/Sq. Mile
5	Ohio River	12,185,000	0.117	75
6	Tennessee River	3,362,000	0.129	82
7	Upper Mississippi River	11,760,000	0.097	62
8	Lower Mississippi River	7,220,000	0.111	71
10	Missouri River	11,483,000	0.035	23
11	Arkansas-White-Red Rivers	6,474,000	0.041	26
	Total	52,484,000	0.066	42

Table 11b.

Imputed NRI estimates of average annual sediment "wash" loads

		HUMAS Estimates			NRI		
#	Hydrologic Region	Erosion Tons/Year	Sediment Tons/Year	Eff. Deliv. Ratio	Est. Erosion Tons/Year	Hyp. Sediment tons/Year	Hyp. Sediment t/mi2/year
5	Ohio River	239,932,000	12,185,000	0.051	254,904,360	12,945,375	80
6	Tennessee River	63,699,000	3,362,000	0.053	26,732,160	1,410,909	35
7	Upper Mississippi River	229,509,000	11,760,000	0.051	283,742,740	14,538,927	77
8	Lower Mississippi River	137,991,000	7,220,000	0.052	110,043,360	5,757,717	57
10	Missouri River	230,440,000	11,483,000	0.050	491,417,420	24,487,703	48
11	Arkansas-White-Red Rivers	126,719,000	6,474,000	0.051	176,426,730	9,013,539	36
	Totals	1,028,290,000	52,484,000	0.051	1,343,266,770	68,560,438	55

Table 11c and Figure 87 present a comparison of HUMUS Project and imputed NRI-based sediment wash load estimates with USGS data on suspended sediments as reported for the Hydrologic Regions in the Mississippi River Basin in the National Water Summary of 1990/1991 by Smith, Alexander, and Lanfear.

The USGS suspended sediment data do not include estimates of reservoir sediment entrapment or of bedload sediment transport. That the USGS suspended sediment loads are generally higher than the HUMUS and NRI estimates of sediment wash may be attributed to the fact that a significant part of the suspended sediment load is derived from instream erosion, mass wasting, and deposition of airborne sediments not accounted for by the estimates of sheet and rill erosion.

On the other hand, the available literature on sediment delivery ratios is largely based on historical comparisons of estimates of erosion rates with recorded suspended sediment data from stream gages. A slight change in the selection of sediment delivery ratios could have markedly changed Tables 11a, 11b and 11c and Figure 87. In the ongoing phase of the HUMUS Project, we intend to use a stream power function to derive new estimates of sediment transport processes. We hope this approach will provide new insights into comparisons between sediment source and delivery estimates.

The reasons for differences between the NRI and HUMUS sediment delivery estimates are probably the same as for the differences in estimated erosion rates. Nevertheless the close correlations between the current condition NRI erosion rates for the Ohio, Missouri, and Arkansas-White-Red Regions are remarkable, given the short-cut method used herein to derive the NRI-based estimates. The low correlations for the Tennessee and Lower Mississippi Regions suggest the need for further research. For example, we need to check with the authors of the referenced USGS report as to whether the USGS estimate of suspended loads in the Lower Mississippi Region include some sediment loading from upstream regions.
Figure 88 is a map showing the preliminary HUMUS Project estimates of sediment wash loads for the 8-digit watersheds in the Mississippi River Basin. Notice that the sediment delivery estimates are particularly high for the Tennessee and Lower Mississippi Regions, areas where the NRI reports erosion for significantly less than half of the contributing drainage areas.

Table 11c.
Estimated average annual sediment “wash” loads

Reg	Hydrologic Region	Humus Preliminary Estimates		
		HUMUS “wash” load t/mi2/year	NRI Imputed “Wash Load t/mi2/year	USGS Suspended t/mi2/year
5	Ohio River	75	80	85
6	Tennessee River	82	35	85
7	Upper Mississippi River	62	77	102
8	Lower Mississippi River	71	57	111
10	Missouri River	23	48	45
11	Arkansas-White-Red Rivers	26	36	31
	Total	26	36	31

Nitrogen and Phosphorous

The preliminary HUMUS Project estimates for movements of nitrogen and phosphorous are based entirely on computations of contributions of organic matter contained in and transported with topsoils detached by erosion. They include no estimates of contributions by fertilizers, animal wastes, urban wastes, industrial discharges, atmospheric exchanges, leaf fall, or any other sources. They are also based on the assumption that all cropsoils are minimum tilled. Thus, they are underestimates of background loads. They represent low levels of nutrient contributions that society probably cannot hope to achieve by any conceivably adoptable set of pollution reduction policies.

Table 12 provides an insight into the implications of our assumptions.

The reason that the percentages for Organic N and Organic P are so similar is that the data are in percentages of total contribution, not actual loads. Though Phosphorous delivery tonnages are much lower than are Nitrogen loads, the percentages of total loads by river basins are so nearly identical that they show as only one line on Figure 89.

Table 12.
Comparing sediment load rates with organic N&P rates.

No.	Hydrologic Region	Percent Total		
		Sed. Wash	Org. N	Org. P
5	Ohio River	23.22	21.14	21.17
6	Tennessee River	6.41	4.64	4.73
7	Upper Mississippi River	22.41	30.69	30.63
8	Lower Mississippi River	13.76	8.11	8.11
10	Missouri River	21.88	26.41	26.35
11	Arkansas-White-Red	12.34	9.01	9.01
	Mississippi River Basin	100.00	100.00	100.00

These data show that soils in the Upper Mississipppi and Missouri Regions have significantly higher levels of organic content than do the soils in the other regions. The soils in the humid warm Lower Mississippi Region have the lowest levels of organic content. Thus, on a ton per ton basis, they provide the lowest share of associated organic matter contributions to the Gulf of Mexico.

This information is illustrated in the maps in Figure 90 for organic nitrogen and Figure 91 for organic phosphorous.

Although deliveries of organic nitrogen and phosphorous are not directly related to streamflow estimates of nitrates and total phosphorous, some insights can be inferred from correlations between these data.

Table 13 and Figure 92 display comparisons between HUMUS Project estimates of delivery of organic nitrogen under low erosion rate conditions to data on nitrate deliveries as published in the USGS report described above.
Table 14 and Figure 93 show similar comparisons between estimates of organic phosphorous runoff and total phosphorous deliveries reported in the USGS report.

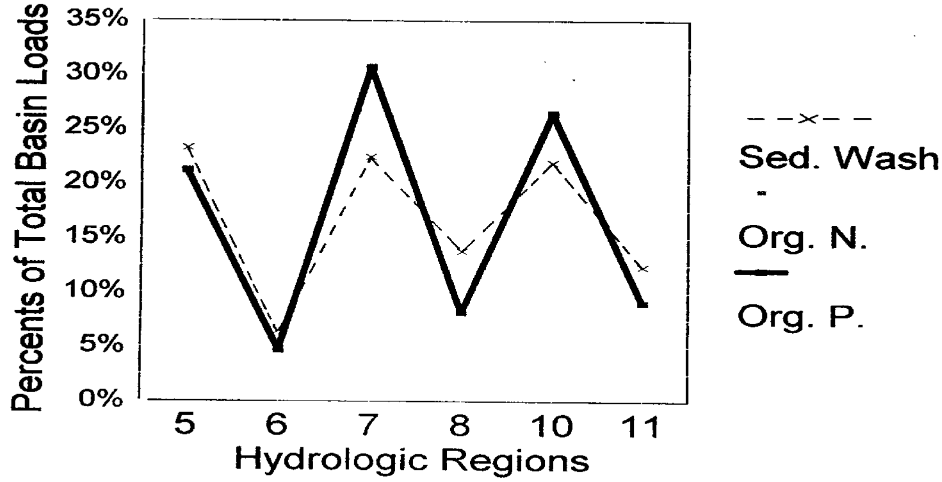

Figure 89.
Comparing sediment, Org. N, & Org. P by hydrologic regions.

Atmospheric wet disposition rate of NADP nitrate (NO3) in 1988 (top) and 1993 (bottom) in mol/m2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

Atmospheric wet disposition rate of NADP ammonium (NH4) in 1988 (top) and 1993 (bottom) in mol/m2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

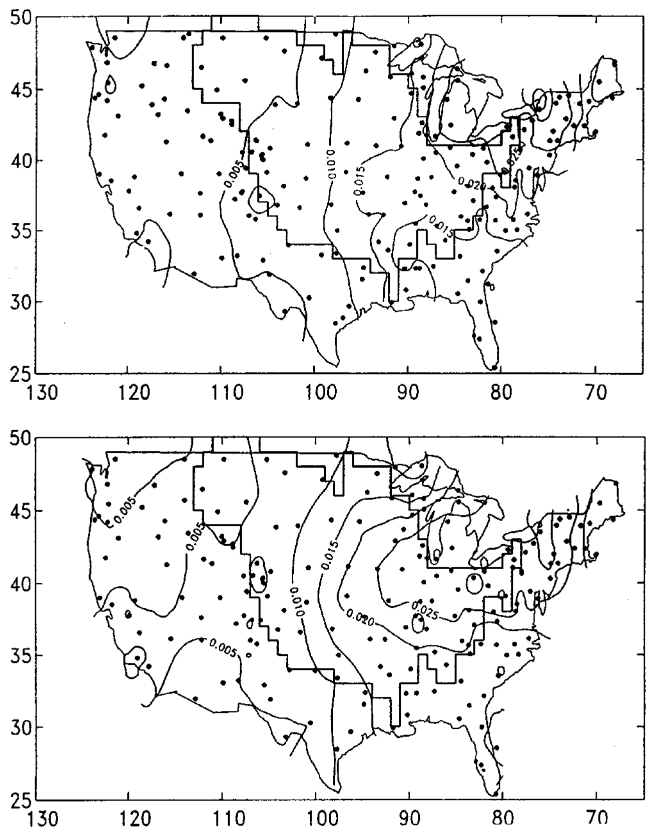

Figure 90.
Organic nitrogen map

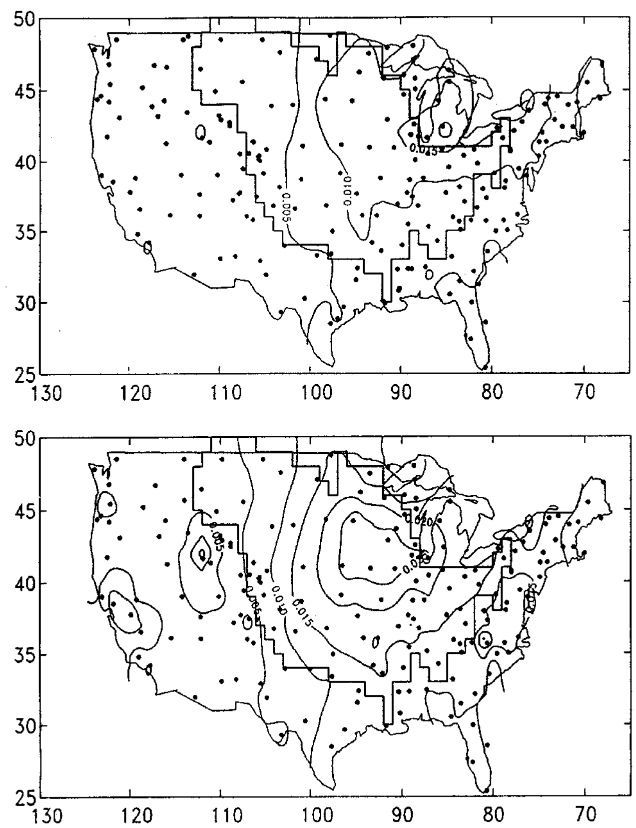

Figure 91.
Organic phosphorous map

Table 13.
Comparing preliminary HUMUS Project estimates with USGS data

No.	Hydrologic Region	Percent Total		USGS Est.
		Avg. Org. N Tons/year	Av. Org. N T/mi2/year	Nitrates t/mi2/year
5	Ohio River	23.22	21.14	21.17
6	Tennessee River	6.41	4.64	4.73
7	Upper Mississippi River	22.41	30.69	30.63
8	Lower Mississippi River	13.76	8.11	8.11
10	Missouri River	21.88	26.41	26.35
11	Arkansas-White-Red Rivers	12.34	9.01	9.01
	Mississippi River Basin	100.00	100.00	100.00

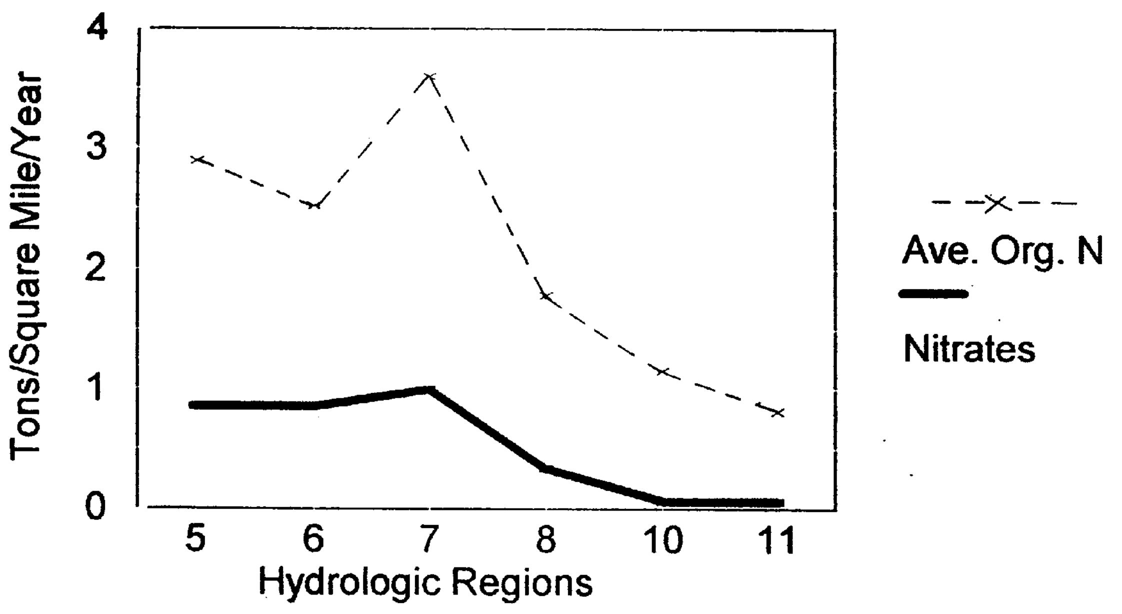

Figure 92.
Comparing organic N with nitrate loads by hydrologic regions.

Table 14.
Comparing preliminary HUMUS Project estimates with USGS data.

No.	Hydrologic Region	HUMAS Preliminary		USGS Est.
		Avg. Org. N Tons/year	Av. Org. N T/mi2/year	Total P t/mi2/year
5	Ohio River	94,000	0.58	0.125
6	Tennessee River	21,000	0.51	0.125
7	Upper Mississippi River	136,000	0.72	0.157
8	Lower Mississippi River	36,000	0.36	0.103
10	Missouri River	117,000	0.23	0.028
11	Arkansas-White-Red Rivers	40,000	0.16	0.039
	Totals	444,000	0.36	0.072

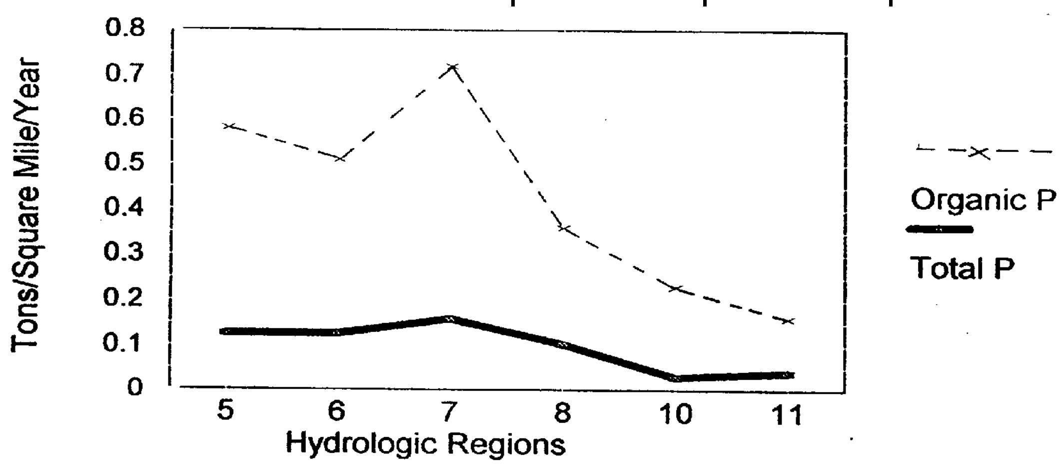

Figure 93.
Organic P runoff vs. Total phosphorous by hydrologic region.

Even though the erosion-related sources of nutrients are only a part of the total load of nutrients to the streams in the Mississippi River Basin, the preliminary estimates of runoff loads of organic N and P are significantly higher than are the USGS streamflow-based records of nitrates and total phosphorous.

This is not at all surprising. This is an indication of the vital importance of instream deposition, reduction, and volatilization of nutrients and of the effects of living organisms in aquatic ecosystems.

Presentation Discussion

Clive Walker (NRCS—Texas A&M University)

No questions after Clive Walker's presentation.